DISCUSSION OF THE DESIGN FOR A FUSION SPACE PROBE - VIPER PULSED FUSION ROCKET

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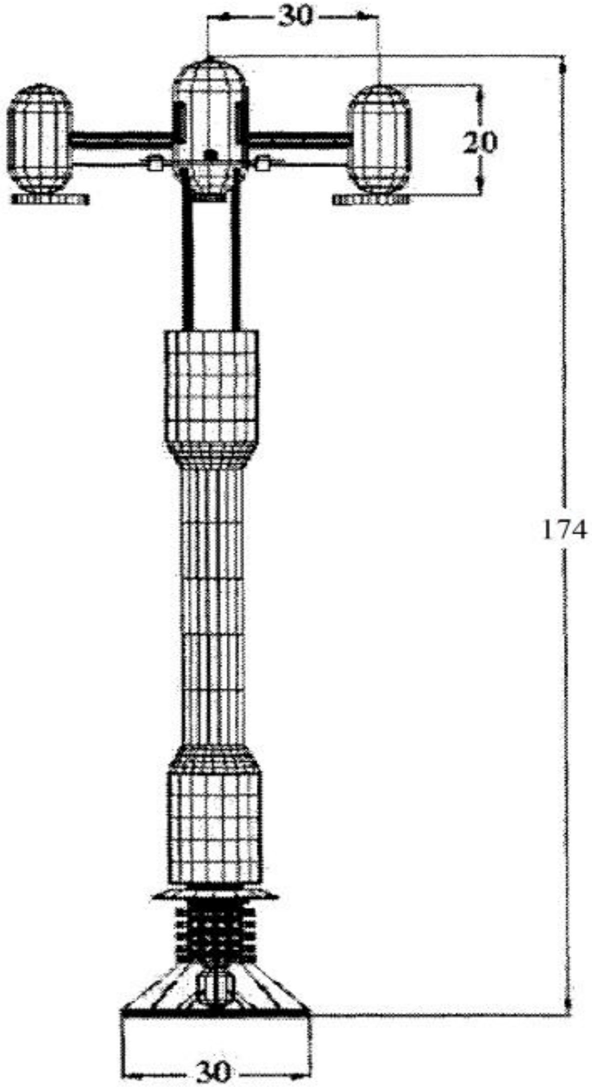
Overview of Prior Fusion Space Propulsion Concepts

A variety of fusion propulsion concepts were surveyed by C. H. Williams and S. Borowski (NASA Glenn), 1997:

Objective of the 1997 survey:

- To provide a top-down, mission-driven approach where desired missions, trip times and payload mass fractions are specified first
- Using this, operation parameters – specific power, specific impulse, structural mass, output power and thrust are determined
- This enables mission requirements to be specified, so better systems can be designed with further refinement
- The basis of the survey was the NASA SEI (Space Exploration Initiative) report (1988-1992)
- **General consensus was that nuclear propulsion technology could shorten trip times and increase payload mass fractions by several orders-of-magnitude – key to outer solar system explorations.**

IEC based concepts: Fusion Ships I & II

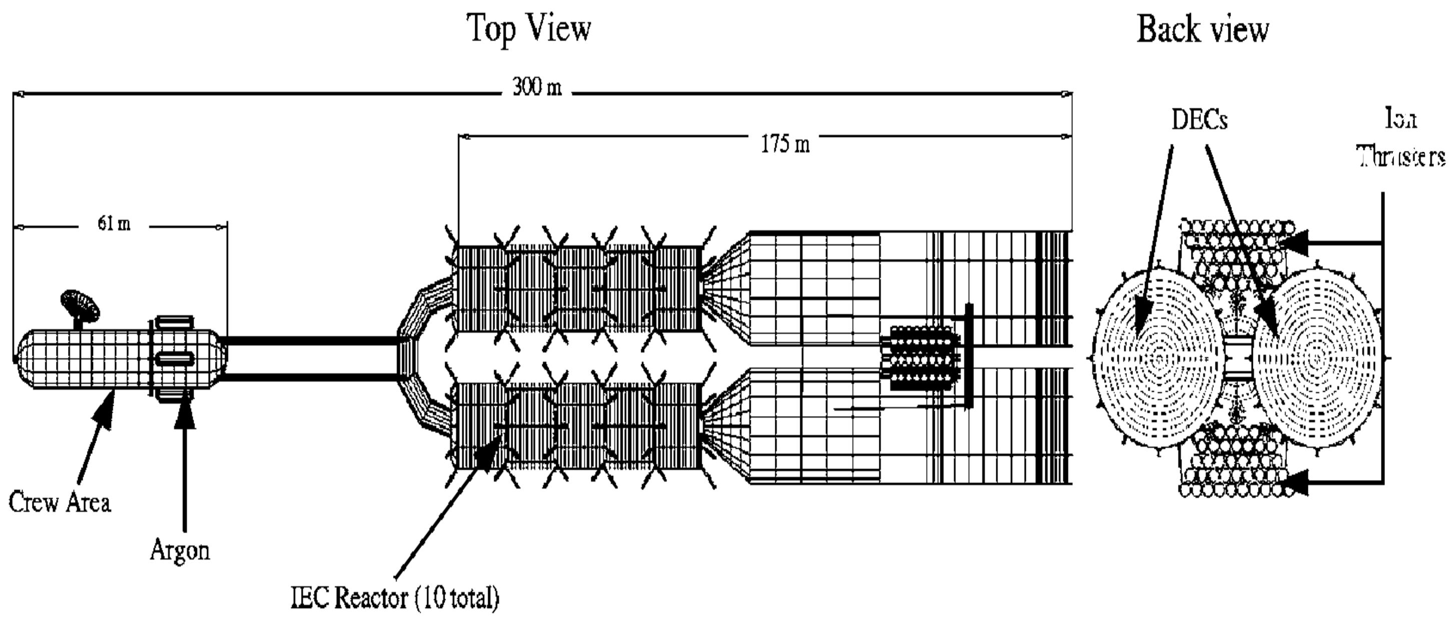


•Consists of 10 D-^{3}He spherical IEC reactors and twin TWDECs

• Produces 300 MW of 14 MeV proton flux, converted to 178 MW of electric power

• 74 MW re-circulates to run the reactors, 100 MW used to drive ion thrusters, remaining rejected as waste heat

• A fusion fuel re-circulation system is operated continuously to separate ^{4}He from the D-^{3}He reactants.

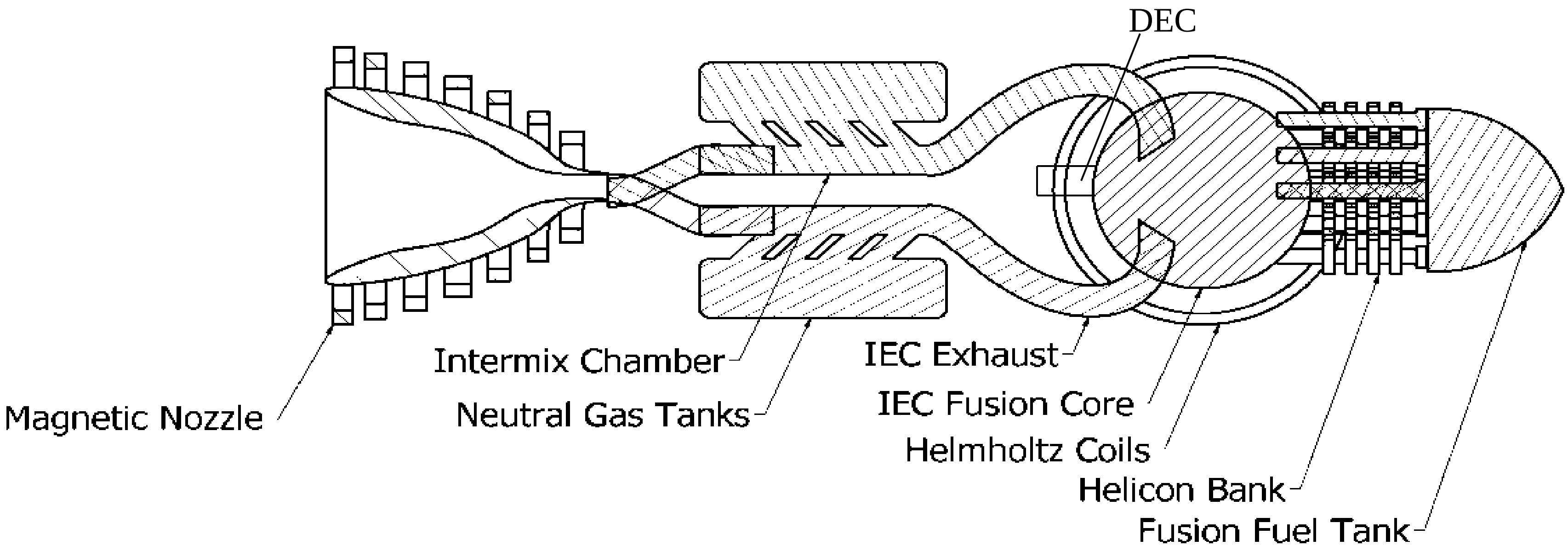


- Twin 175 m long assemblies comprising of 5 D-^{3}He spherical IEC reactors and a TWDEC each
- Generates 1394 MW of 14.7 MeV proton flux, converted to 1197 MW of electric power
- 242 MW of this re-circulates to run the reactors and 750 MW drives the ion thrusters
- A fusion fuel re-circulation system operates continuously
- Argon ion thrusters with specific impulse of 35,000 s and efficiency of 90% are employed

Fusion Ships I & II

	Fusion Ship I	Fusion Ship II
Overall Mass (Metric T)	500	500
Overall Length (m)	174	300
Number of crew	10	10
Thrust Power (MW)	86	750
Reactor Gain	4	9
Reactor Power (MW)	296	2178
Thrust system	Krypton ion	Argon ion
Specific impulse (sec.)	16000	35000
Jupiter one way trip time (days)	400	210

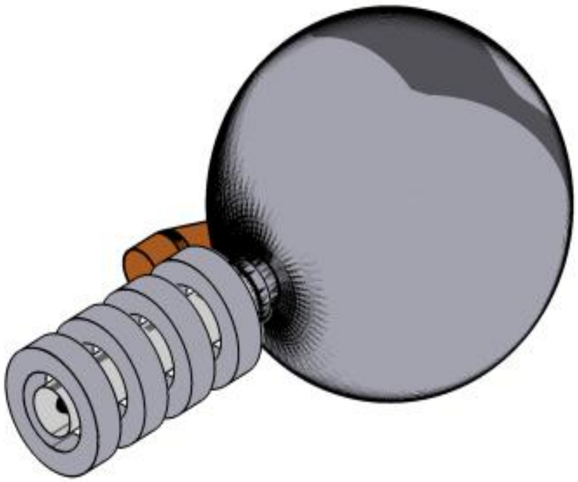
VIPER Schematic

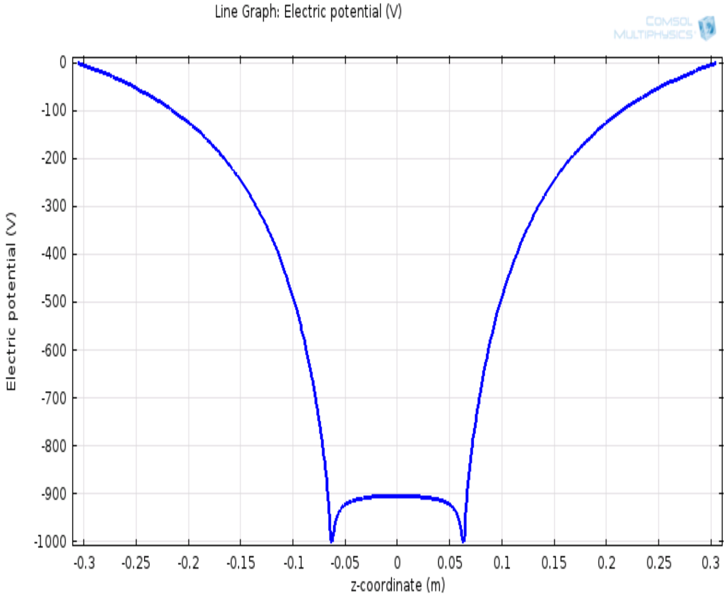


- The IEC reactor is fed highly ionized p-^{11}B fuel by a permanent magnet helicon array
- Anisotropic alpha particles produced - 10% directed to a DEC to produce electric power required to run reactors and for station-keeping, rest are magnetically collimated by a pair of Helmholtz coils, quasi-equilibrated with a neutral propellant such as hydrogen and exhausted through a magnetic nozzle to produce thrust
- Launch mass of 30 MT and total power production of 360 MW
- Variable specific impulse system enabling a variety of missions

Inertial Electrostatic Confinement

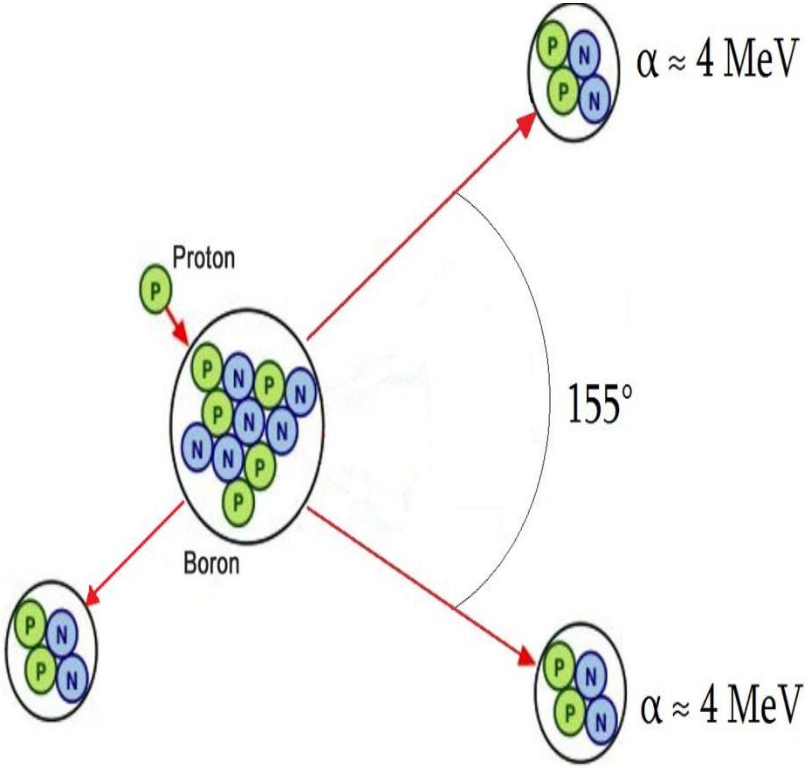
- Spherical electrostatic potential trap used to collide and fuse ionized hydrogen and boron-11.
- Mitigates thermal losses since the potential well establishes and maintains ion confinement
- Confinement times can be increased using multi-grid configuration – recently demonstrated experimentally by Ray Sedwick at U of Maryland.
- Prior shortcomings in plasma density – hence helicon is used to provide high density plasma
- This helicon-fed IEC design is derived from HIIPER, an experimental electric propulsion system under evaluation at Univ. of Illinois





p-^{11}B: Nonradioactive Fusion Power

- Safe, naturally abundant non-radioactive Boron-11 fuel
- Highly charged fusion products (3α @ 8.7 MeV)
- Aneutronic – minimal shielding from neutron flux required
- Ideal for space-based power systems



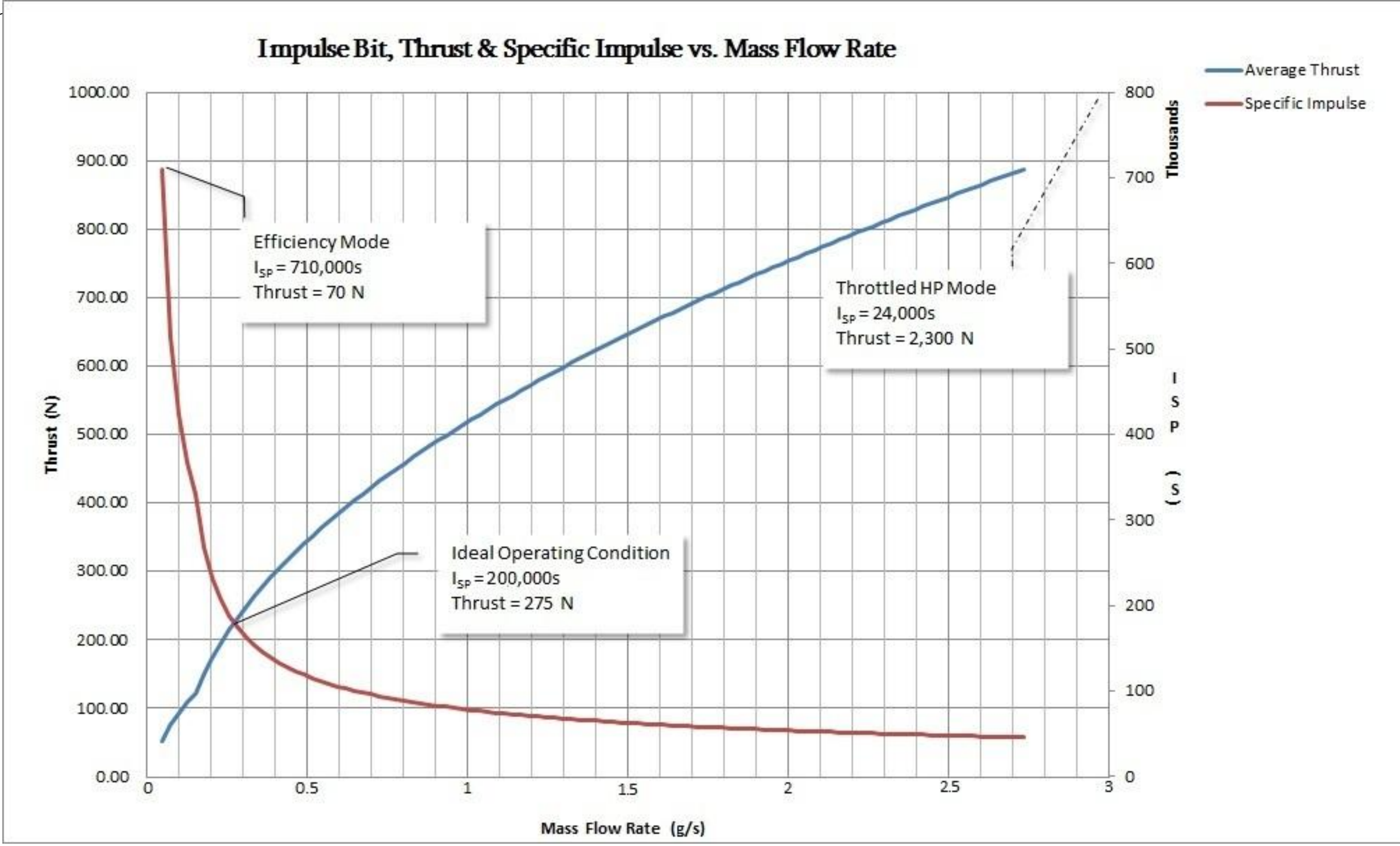
$$p + {}^{11}B \rightarrow 3\ {}^{4}He + 8.7\ MeV$$

System Parameters

	Power (kW)	Mass (MT)
	Primary Systems	
Helicon Array	1600	2
IEC	18000	8
Magnetic Nozzle	50	1.5
Capture Assembly	100	.5
M_{POW}(Marx, HPDEC, transformers)	-	4.5
	Secondary Systems	
Structure, shielding	-	7
Heat Radiators	1500	4
Injectors, tanks, lines, etc.	<1	.75
Guidance, computers, etc.	<1	.15
Scientific Payload	250	1.5
Total	**21,500**	**29.9**

Salient features of VIPER

- A plentiful and non-radioactive fuel - p-^{11}B is used
- Aneutronic fusion – reduced neutron flux shielding
- Extremely high specific impulse: 10^4 – 10^6 s
- Realizable near-term technology – since IECs and Helicons are well-researched experimentally
- VIPER is the first step towards manned missions in the future
- Variable specific impulse enables a variety of missions



Ideal	f_{pps} = 12, τ_p = 62.5 ms. $\dot{m}$ = .25 g/s
T_{AVG}	275 N
I_{SP}	200,000 s
$\dot{m}$	2.584 x10 $^{-4}$ kg/s

Mission capabilities

Fast Deep Space Probe

Pluto arrival < 1 year

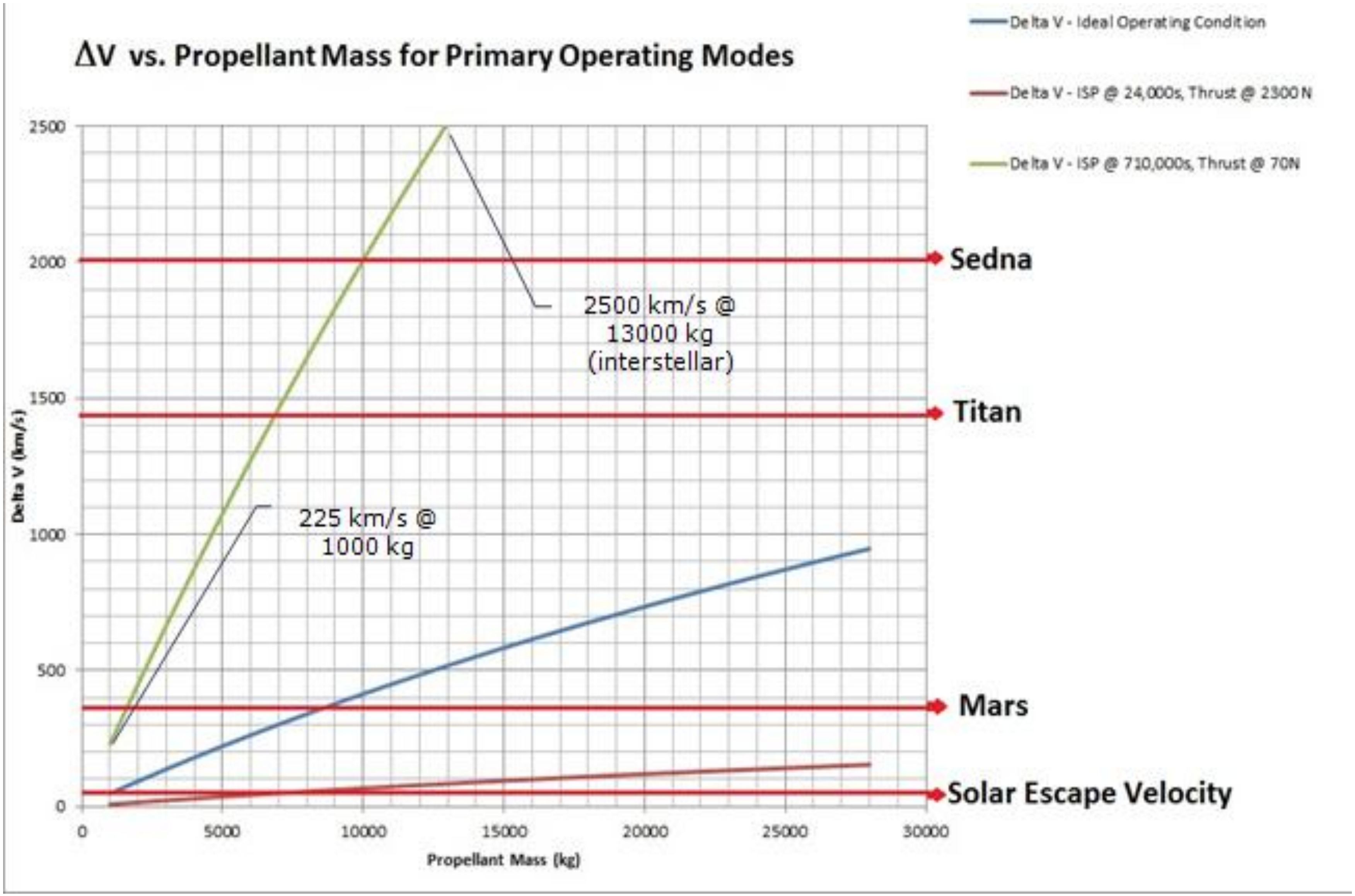
Sedna (518 AU) arrival < 5 years

Martian Heavy Lift

200 MT cargo ~ 120 days

Reusable Science Vessel

Extremely high ΔV allowing maneuverability, orbital transfers, sample return, etc.



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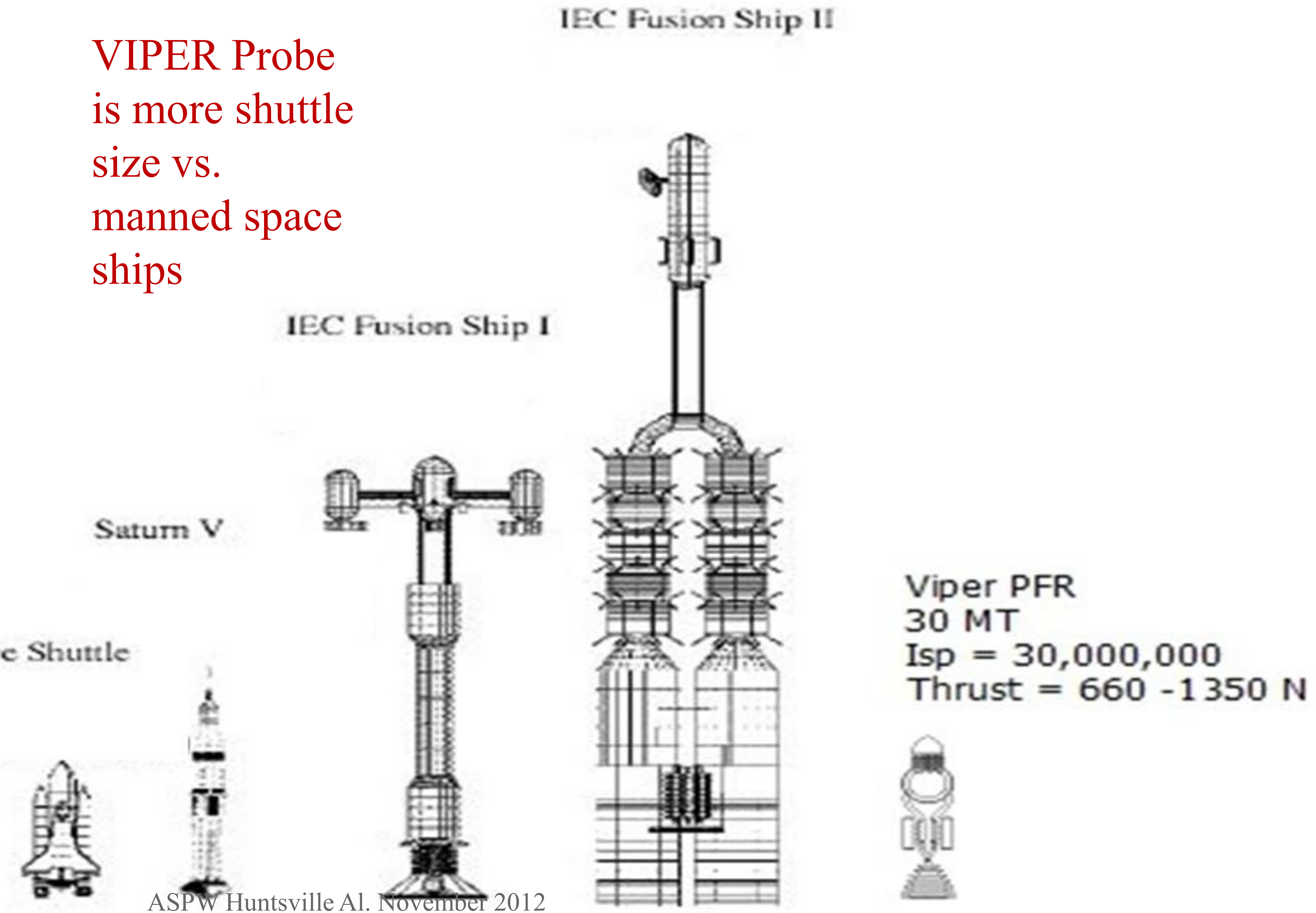
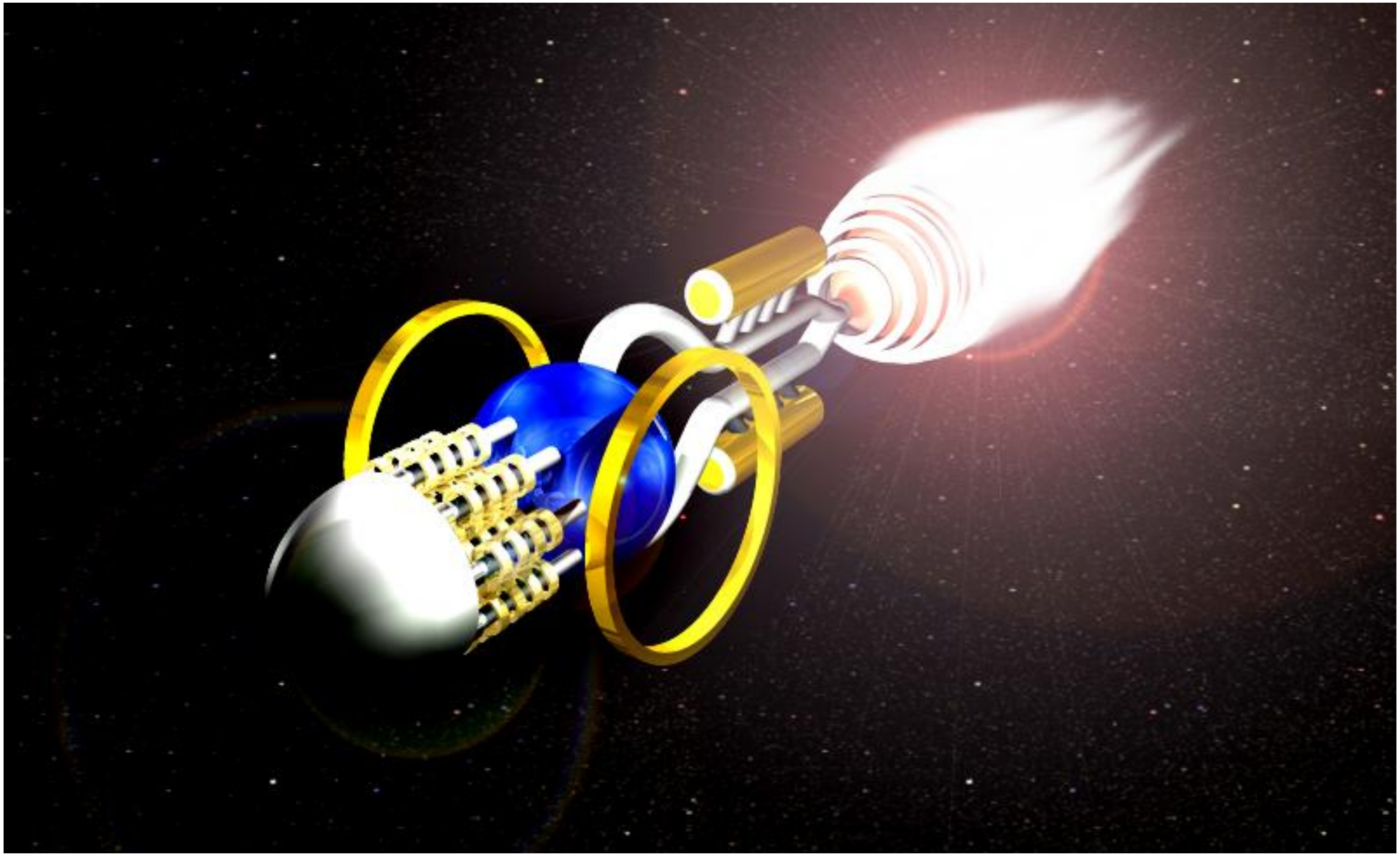
VIPER Probe is more shuttle size vs. manned space ships




Artist’s conception of VIPER (P. Keutelian, 2011)

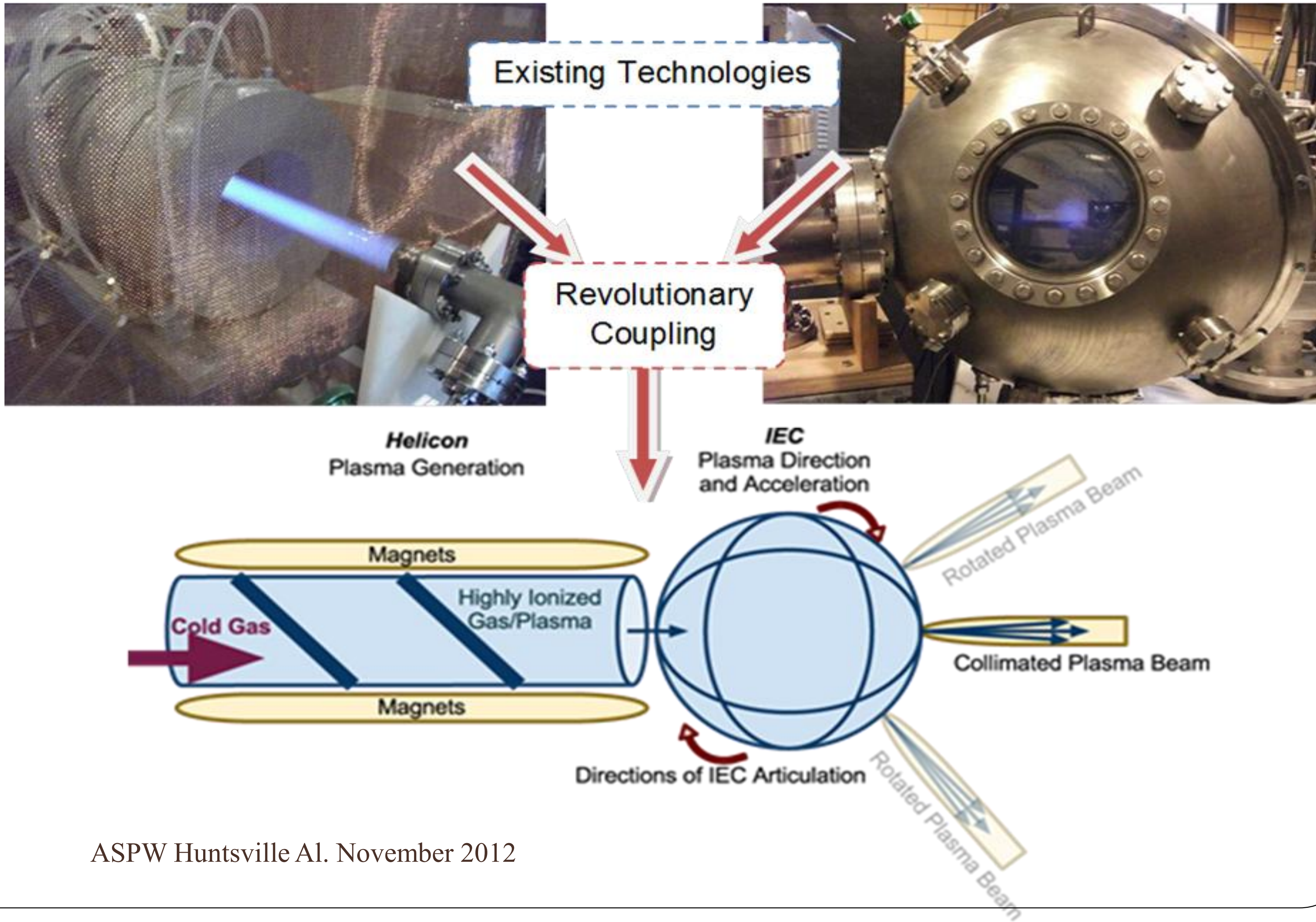
Helicon-Injected Inertial Plasma Electrostatic Rocket (HIIPER) – development path to Viper

Objective – to develop a near-term electric thruster that uses much of the same physics as the VIPER fusion rocket. In this way progress towards VIPER can be made with a near-term pay-back

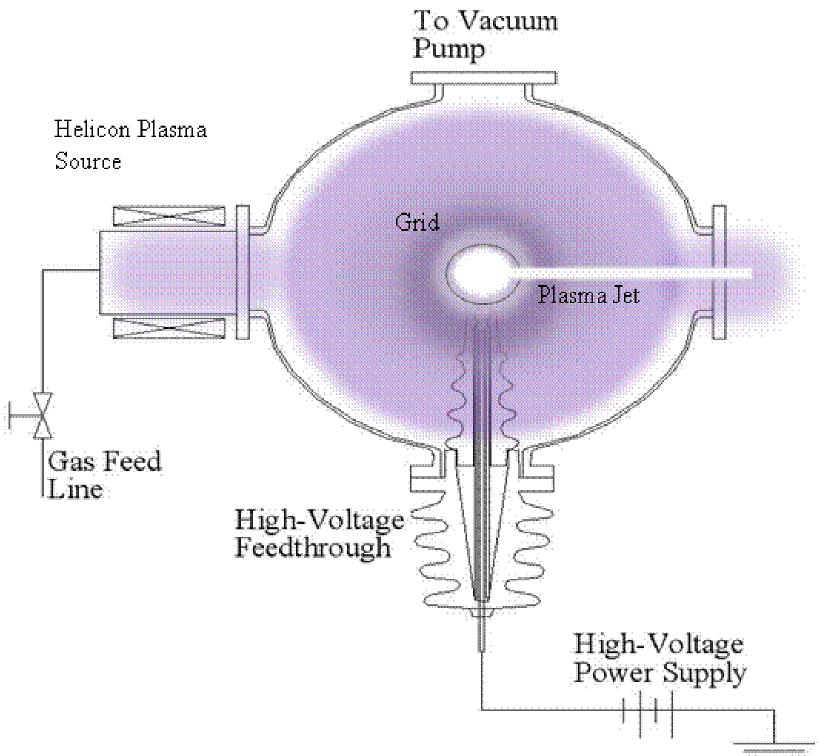
Introduction to HIIPER

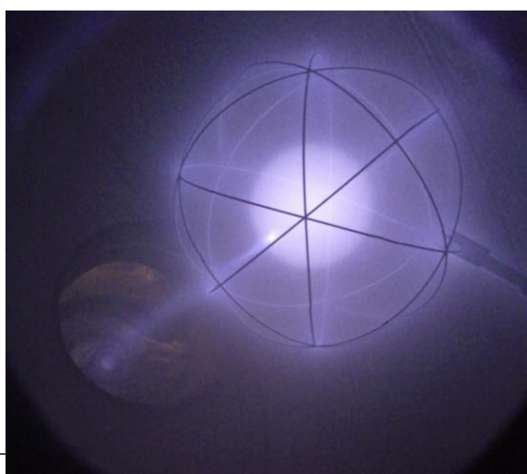
- Helicon-injected IEC-Class Plasma Thruster
- Designed for interplanetary and deep space missions
- Highly Scalable (Variable specific impulse)
- Compact
- Simple design using commercially available helicon and IEC device
- Gas Versatile
- Reduced erosion of grid and plasma facing components – higher operational lifetime
- Highly efficient due to nearly complete ionization of propellant by the Helicon source

HIIPER Concept



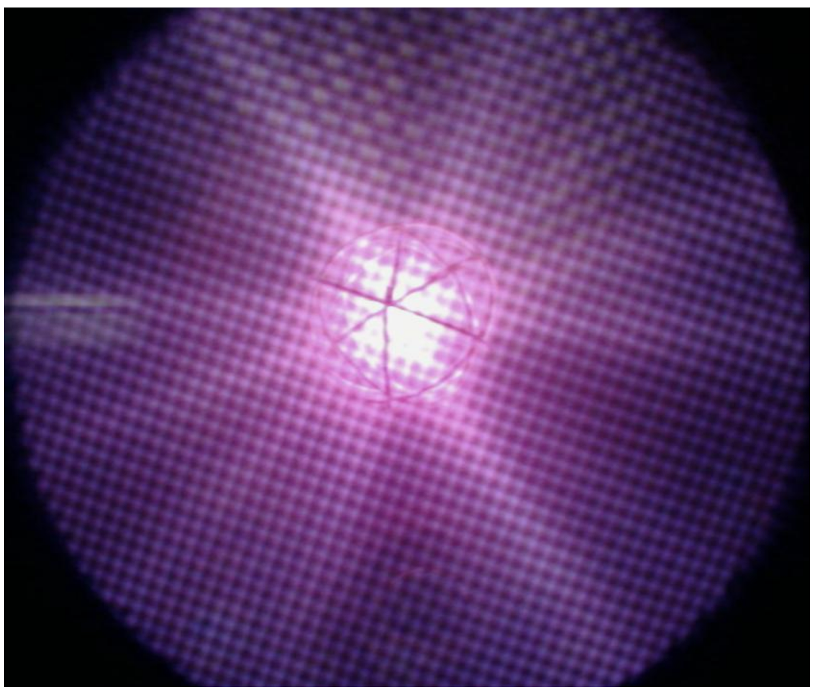
HIIPER Concept

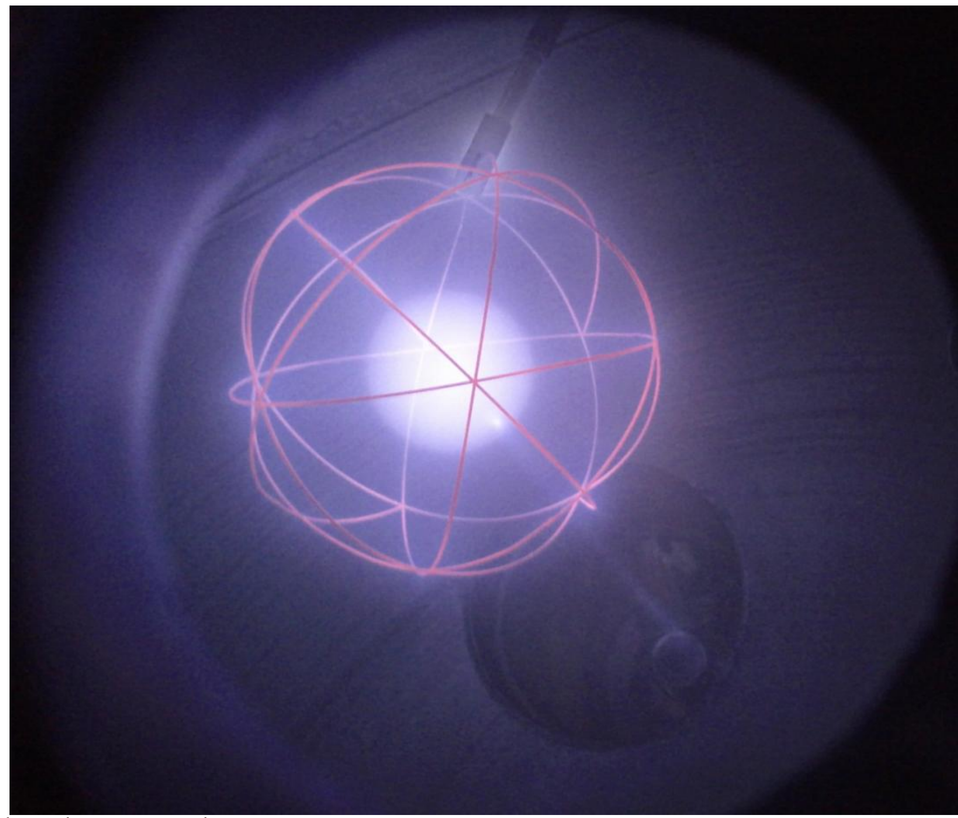




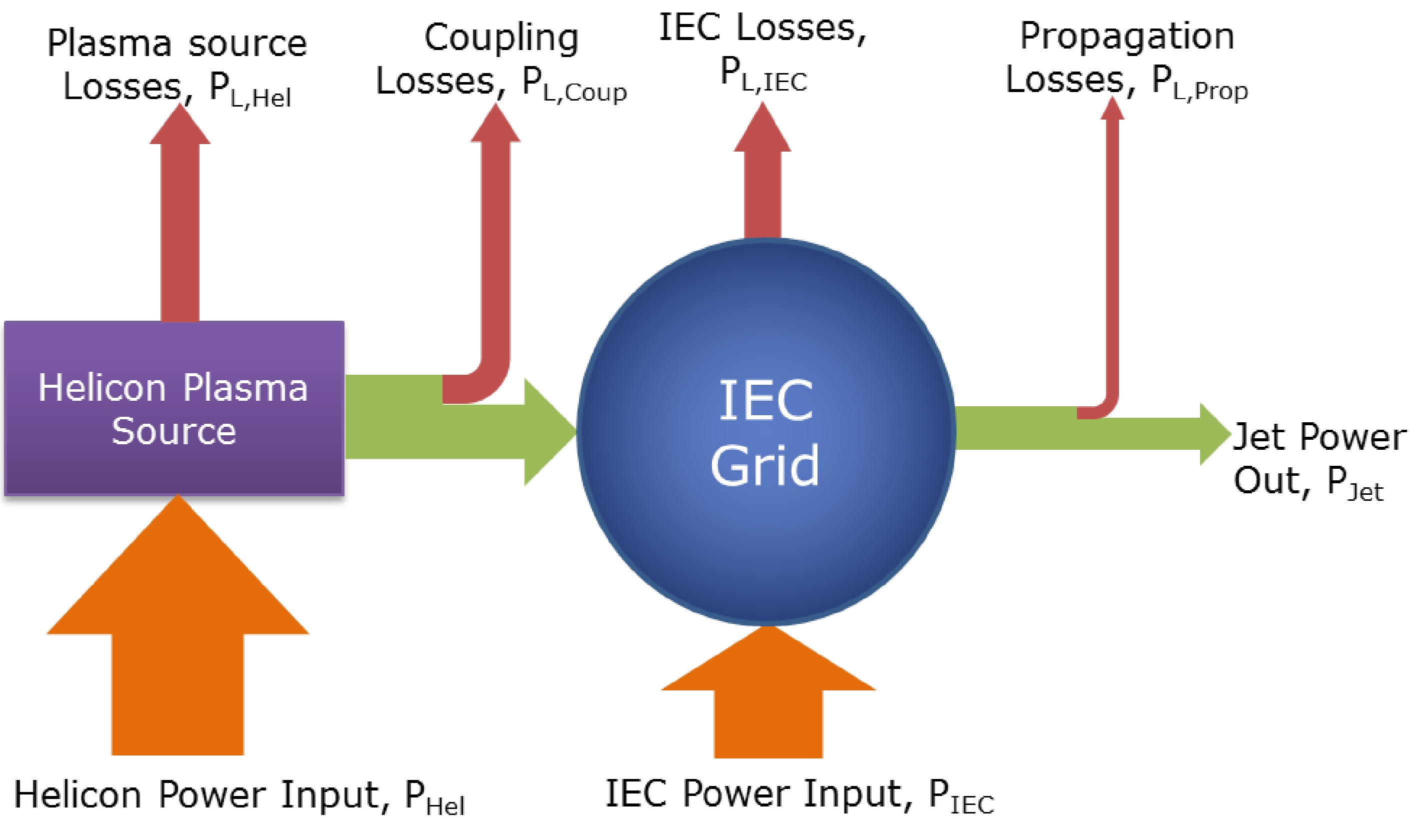
- High density plasma is produced by the Helicon source
- Inertial electrostatic confinement accelerates plasma using a spherical diode configuration
- A thin plasma beam is produced due to asymmetry in the central cathode grid in “jet mode” operation.
- This plasma jet contains a significant fraction of the input energy

Background – IEC Operation Modes





Power balance



$$P_{Hel} + P_{IEC} = P_{Jet} + \{P_{L,Hel} + P_{L,Coup} + P_{L,IEC} + P_{L,Prop}\}_{Losses}$$

Thrust estimate for experiment

Estimate for Argon:

Power into the helicon: 300 W
Power into the IEC: 30 W

At a voltage of 2kV in the IEC, exhaust velocity of the jet = 83000 m/s

Maximum theoretical thrust: 392 mN
Allowing for 50% losses, thrust = 196 mN

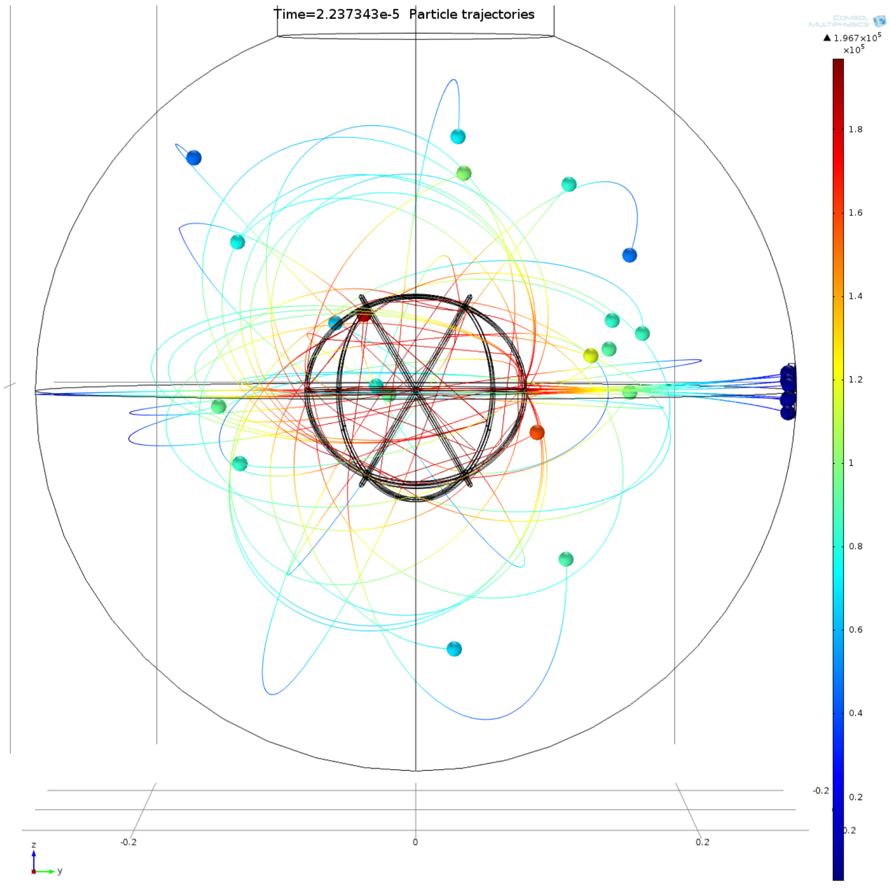
HIIPER produces a thrust of 0.6 mN/W

NOTE: Conventional hall thruster would produce 0.06 mN/W.

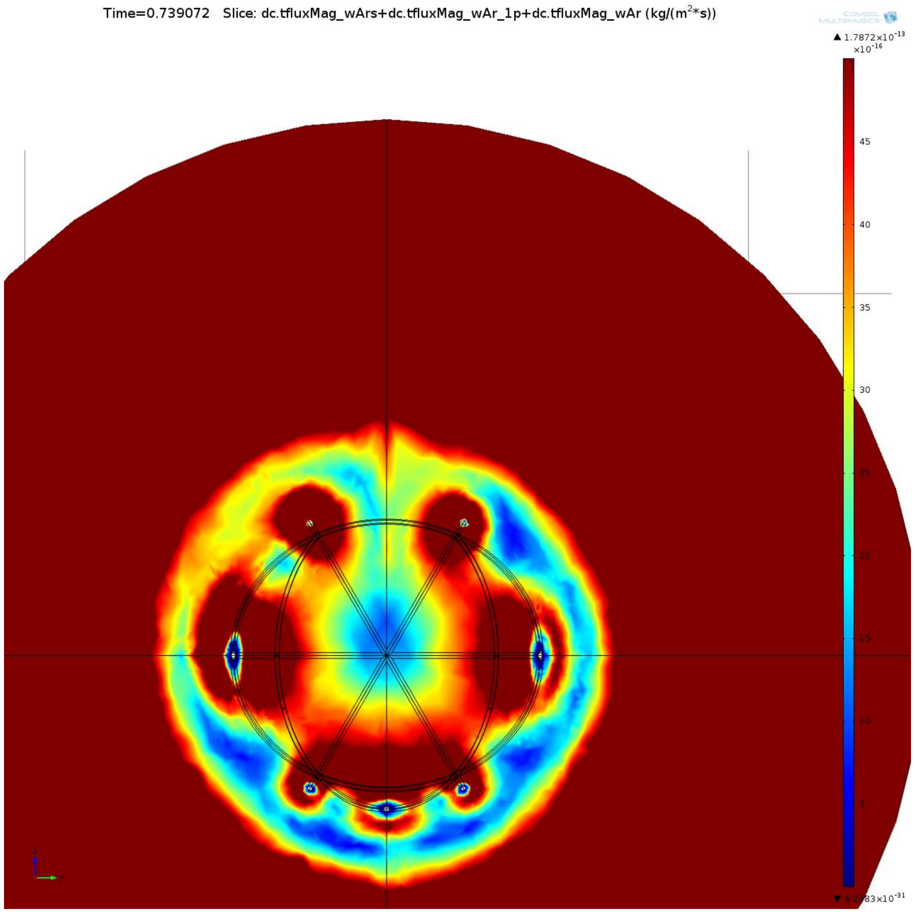
Preliminary Work - Simulations

COMSOL Multiphysics:

Particle Trace:



Plasma Package:



Preliminary Work – Modeling of Helicon

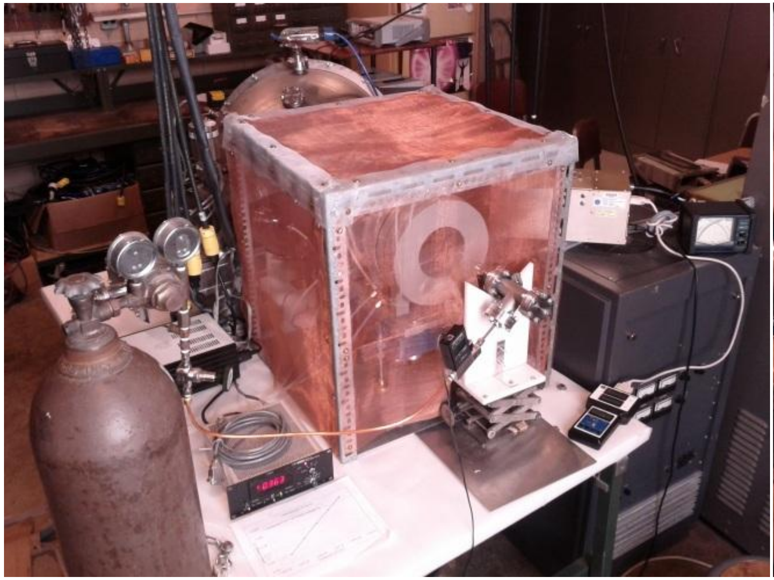
- A set of coupled rate equations have been created to model the particle balance of the different species (e.g. neutrals and ions) and power carried by each species.

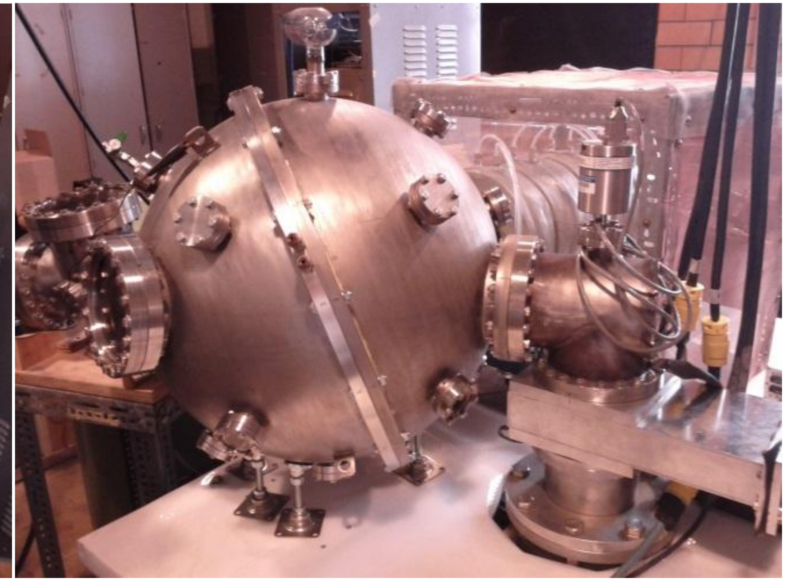
$$\underbrace{\frac{dN_n}{dt}}_{\frac{Particles}{s}} = \underbrace{[N_{n,in}] - [N_{n,out}] - [N_{n,ioniz}]}_{\frac{Particles}{s}}$$

$$\underbrace{\frac{dN_i}{dt}}_{\frac{Particles}{s}} = \underbrace{[N_{n,ioniz}] - [N_{i,out}]}_{\frac{Particles}{s}}$$

$$\underbrace{\frac{dN_e}{dt}}_{\frac{Particles}{s}} = \underbrace{[N_{n,ioniz}] - [N_{e,out}]}_{\frac{Particles}{s}}$$

Facilities

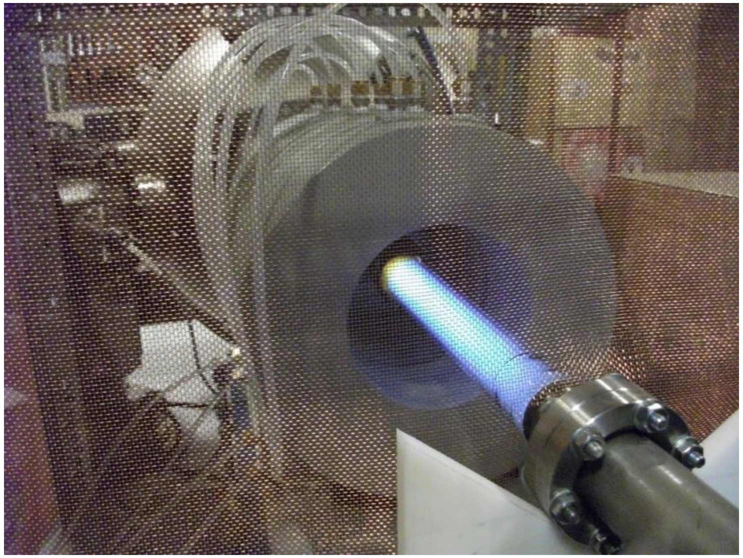


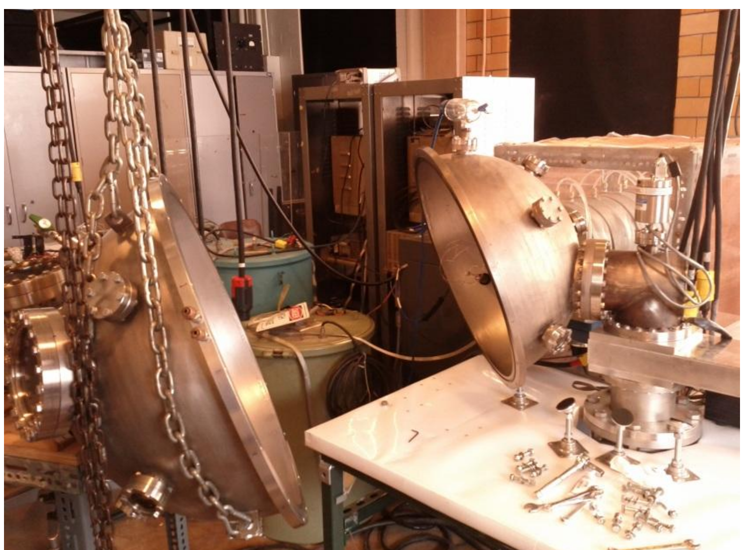


<u>Vacuum System</u>

- 22 inch spherical stainless steel IEC chamber
- Base pressure <1x10^{-6} Torr, typical operating pressure ~ 1 mTorr
- Choice of argon, nitrogen, hydrogen gases

Facilities





Helicon Plasma Source

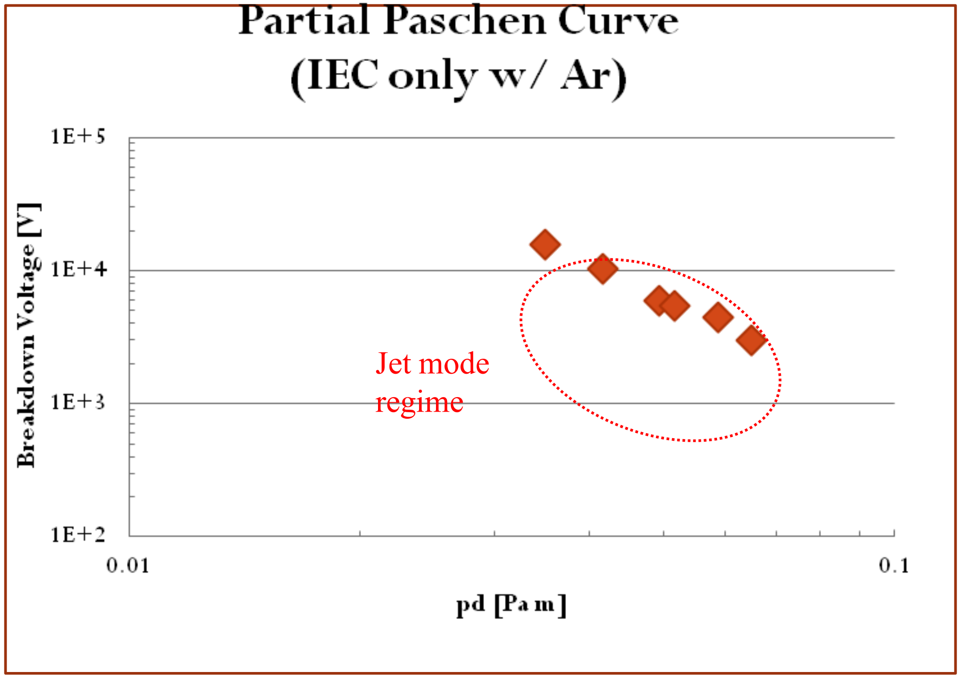
- 13.56 MHz RF power supply 1.2 kW max power with 1 kW max auto-matching network
- Quartz tube with copper strap m=+1 helical antenna
- 1200 Gauss maximum electromagnets – water cooled

IEC Device

- 50 kV, 50 mA power supply, 1 kW max power
- Custom built stainless steel grid

Initial Experiments

- Discovered jet mode pressure regime (~0.5 to 2.0 mTorr for visible jet)
- Made measurements of plasma floating potential of jet (up to -5.5 kV at -10.5 kV IEC grid operation – 1.5 mTorr)

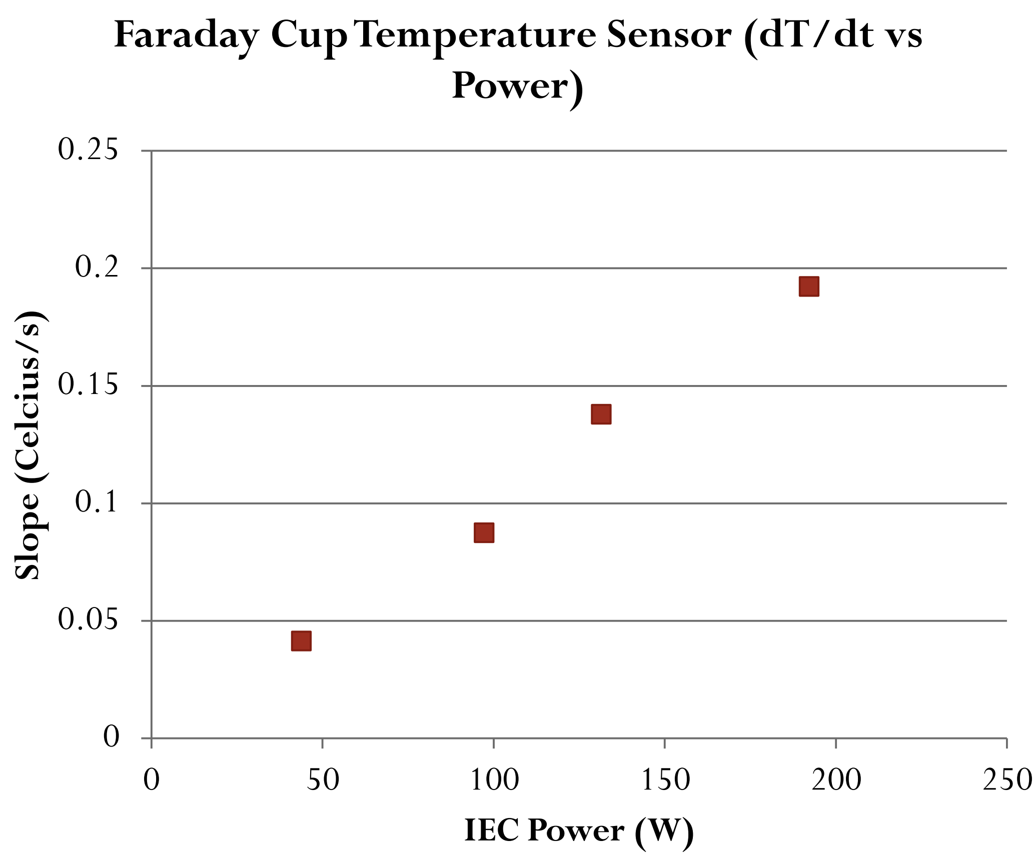


Faraday Cup

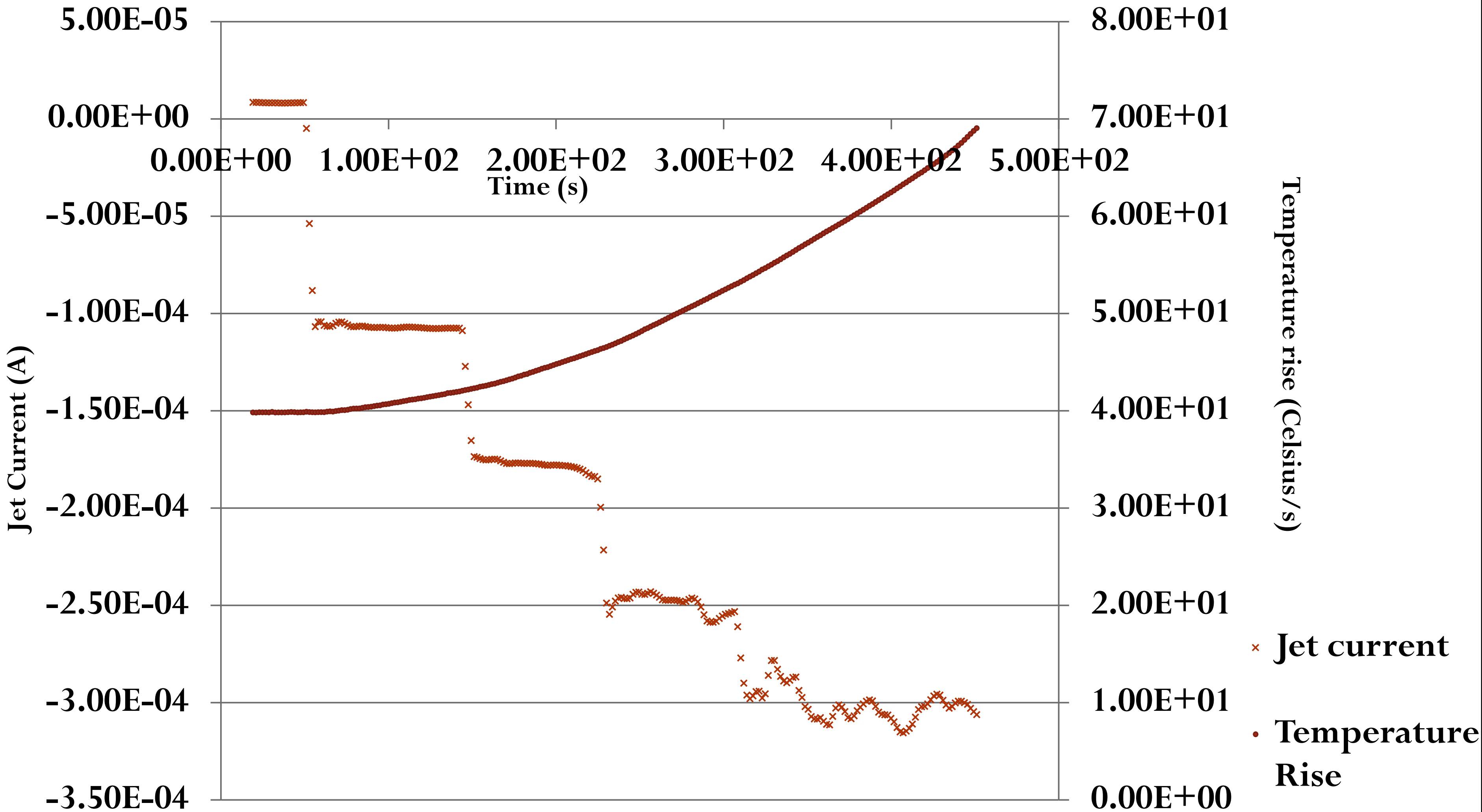
- Measures the total charge flow of the jet
- The cup was made large and robust to deal with the high current and voltages while being able to dissipate heat quickly enough to avoid damage to the structure.
- The cup has been custom-fabricated from alumina ceramic, stainless steel and aluminum.
- The design also implements an outer grounded sleeve around the inner cup.
- A resistance temperature detector (RTD) was used to measure the temperature increase on the faraday cup.

Rate of Temperature Rise with Increasing Input Power

- This data can be used to estimate the thermal power of the jet

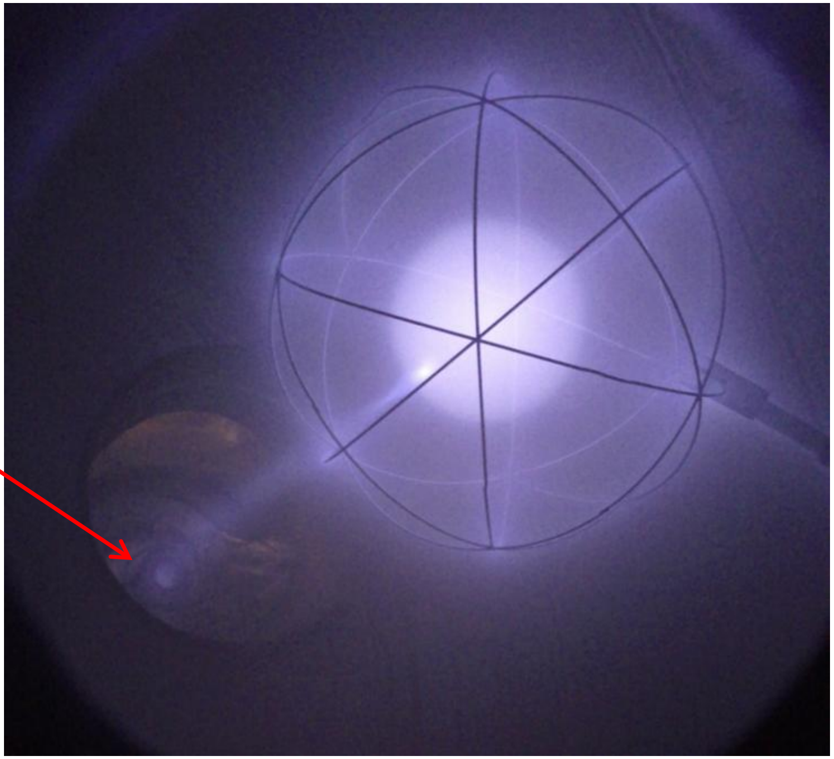


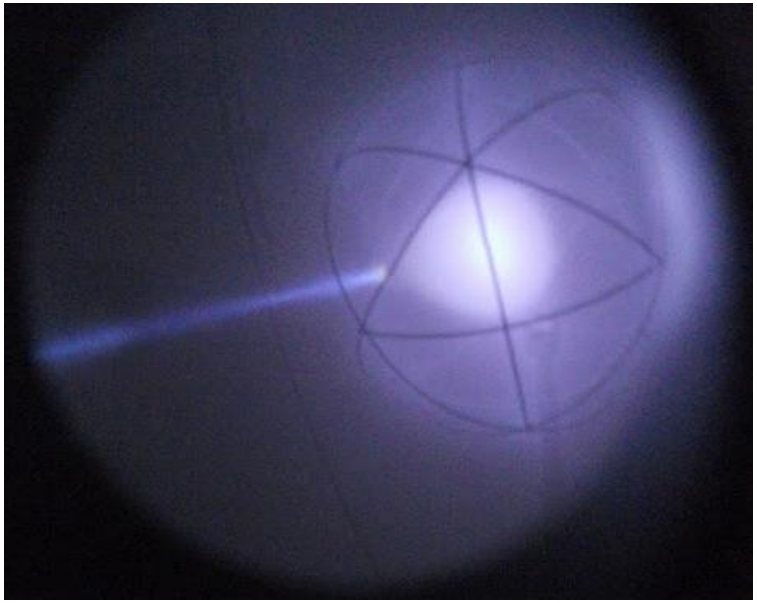
Current Measurements



Observations

Jet in to Faraday cup





Interesting structure of the plasma

Summary

- HIIPER is a Helicon-fed IEC thruster
- Decoupling of Helicon and IEC stages enables variable impulse
- Improved fuel economy
- Light-weight device and simple in design
- Gas versatile
- Vectored thrust – ability to rotate the IEC grid allowing control over the plasma jet direction
- Reduced erosion – high lifetime
- Can be upgraded to a future fusion spacecraft

Conclusion

- VIPER is an unmanned fusion probe concept
- Simple design with fewer assumptions compared to previous manned propulsion concepts
- Use of p-^{11}B fuel facilitates aneutronic fusion - hence less mass required for radiation protection
- Most of the fusion energy is used for direct thrust conversion, 10% to power reactor
- Performance characteristics are significantly higher than prior concepts

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Thank you for your attention!

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